The Influence of Sodium Carbonate on Soil Forming Processes and on Soil Properties

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It is a generally accepted fact that water soluble salts, especially the sodium salts, are responsible for the undesirable properties and low fertility of salt affected soils. Among the various sodium salts sodium chloride, sodium sulphate, sodium bicarbonate and sodium carbonate play the most important role in salt affected soils. Two main groups of these soils may be distinguished:

1. Soils affected by neutral sodium salts (sodium chloride, sodium sulphate);
2. Soils affected by sodium salts capable of alkaline hydrolysis ($NaHCO_3$, Na_2CO_3, Na_2SiO_3).

These two great groups have been distinguished in the course of the development of soil science and soil classification. Soils belonging to the first group have mainly been named *saline*, and those of the second group: *alkali* soils. These two main types differ not only in their chemical character but also in their geographical and geochemical distribution, in their physical, chemical, physico-chemical and biological properties. The methods used for their reclamation and agricultural utilization are also different.

It is evident that in Nature the various sodium salts do not occur absolutely separately in soils. In most cases, however, either the natural sodium salts or the ones capable of alkaline hydrolysis exercise a dominating nfluence on soil forming processes and soil properties.

The effect of neutral sodium salts on soils

In arid regions, deserts and semi-deserts, most strongly saline soils (having several per cent of water soluble salts in their profile and millimho values higher than 10) contain mainly NaCl and Na_2SO_4. In Russian literature this group of soils is denominated *chloride and/or sulphate solonchak*. Saline soils mainly belong to this group. As a rule, these soils occur under dry conditions in large arid and semiarid regions in Eurasia, North Africa, in the western part of North and South America and in the central part of Australia.

The accumulation of NaCl and Na_2SO_4 takes place in varying degrees in the soil profile. In many cases the salinization process is so intensive that a thinner or thicker salt crust has formed on the soil surface and several per cent of salts may be found in the various horizons of the soil profile. When referring to saline deserts we can hardly speak of "soils" because those strongly saline formations are completely devoid of the most essential property of soils, that is, of fertility.

It is evident that all properties of saline soils are conditioned by the high salt content.

In these soils the soil solution is practically saturated with those salts and, what is more, the salts occur — in crystalline or non-crystalline forms — in the solid phase. If these soils have appreciable clay fractions, the soil colloidal properties are also determined by the high electrolyte concentration.

The general geochemical tendency of the accumulation of various sodium salts was studied by KOVDA [27, 28] and it is schematically shown on Figures 1 and 2. It may be clearly seen in the Figures that parallel with the increasing total amount of sodium salts in high concentrations, the neutral sodium salts become dominant in soils and in ground waters. Besides the neutral sodium salts the sulphates and chlorides of alkali earth metals may also be present in considerable quantities.

Salt affected soils formed under the influence of the above mentioned salts do not always contain such a high amount of water soluble salts as may result in the appearance of salt efflorescence on the surface.

Depending on the salt concentration, various types of saline or solonchak soils develop.

As a rule, the profiles of saline or solonchak soils have no structural horizons. In most cases, no abrupt boundaries may be observed between the individual horizons. They can hardly be separated morphologically.

The effect of sodium salts capable of alkaline hydrolysis on soils

When sodium salts capable of alkaline hydrolysis are discussed — both in literature and practice — usually the effect of sodium carbonate or bicarbonate is emphasized. However, we must not focus our attention solely on the effect of these compounds when striving to elucidate the soil processes. It is fairly evident that in addition to Na_2CO_3 and $NaHCO_3$, other compounds capable of alkaline hydrolysis also play an important role in the formation of alkali soils. Sufficient knowledge of the nature and dynamics of these other compounds and processes is still lacking. Many authors (GEDROITZ [14], 'SIGMOND [39], KELLEY [23], KOVDA [25 26], SZABOLCS [44], SZABOLCS—DARAB [47], ARANY [4]) have pointed out the importance of silicon compounds contained in soils, as well as in surface and ground waters in the processes of the formation of alkali soils. Although it has been generally accepted that silicon compounds, especially those formed with sodium and capable of alkaline hydrolysis, play an important role in alkali soils, a thorough study of these compounds has been practically neglected. In chemical analyses most of the methods used in practice to determine alkalinity express it as Na_2CO_3. The exact role played by other compounds capable of alkaline hydrolysis in alkali soil formation has not been elucidated though it might be of importance even if the dominant role of Na_2CO_3 is unquestionable.

It may be clearly seen in Figures 1 & 2 that, as a rule, the effect of sodium salts capable of alkaline hydrolysis is associated, to a higher degree, with lower salt concentrations than that of neutral sodium salts. In spite of the fact that according to Figure 2 this form of alkalinization is mainly linked with a salt content of 0.2—0.7 per cent, under particular natural conditions it may be observed also in the case of considerably higher salt contents. For example in India, Pakistan, Iraq and Armenia extensive areas

may be found where the salt content of the soils amounts to several per cent and yet the dominant role is played by sodium carbonate. The fact that this seeming anomaly occurs so often may be explained by the local natural conditions. In many cases the parent materials (quite frequently Tertiary formations among them) and the peculiarities of weathering ensure a considerable sodium carbonate supply. Even more often, the ground waters are mineralized to a greater or lesser degree and play an important part in soil formation as the main sources of alkalinity. The formation of soils of high sodium carbonate content (for instance in Central Africa in the environment of lake Chad (CHEVERRY [8], West Siberia [12], Central America, Argentine and even in Hungary) may be explained mostly by hydromorphic soil formation processes. Under relatively humid natural conditions vast areas of salt affected soils of the sodium carbonate type develop.

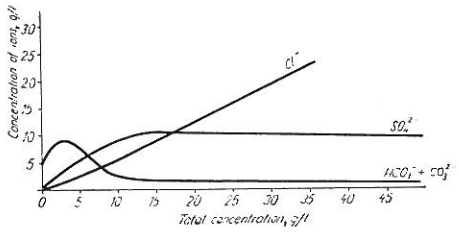


Fig. 1

Relationship between alkalinity and salt concentration in the ground water (after KOVDA)

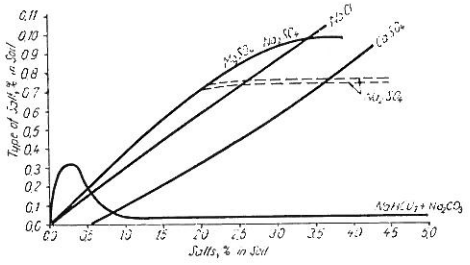


Fig. 2

Relationship between the soil's degree of alkalization and the accumulation of alkaline salt (after KOVDA)

a) The formation and accumulation of sodium carbonate in soils

During the history of soil science many authors have studied the processes and the conditions leading to the formation of sodium carbonate in soils. Various theories have been elaborated and disputed and numerous literary sources discuss these questions. (HILGARD [19], TREITZ [53], 'SIGMOND [39], MURAKÖZY [32], KELLEY [23], ARANY [4], SCHERF [38], VERNER & ORLOVSKI [58], KOVDA [26], SZABOLCS [41] and others.) It has become clear that sodium carbonate may be formed in soils in several ways, by different processes. Therefore it may be said that although some of the above mentioned scientists and their followers strived to verify the exclusiveness of one or another theory of sodium carbonate formation in soils and to disprove or to belittle the importance of sodium carbonate formation processes described by others, practically every theory has its justification and even importance under given circumstances and at certain times. Thus we have to agree with KELLEY, KOVDA and ARANY who suggested that sodium carbonate may be formed in soils in the following ways:

1. By the ordinary weathering process of the earth crust, that is, by the interaction of silicates and CO_2 containing water. During this process bicarbonates of Ca, Mg, Na an K are formed. Upon evaporation of the resulting solutions, Ca and Mg carbonates are precipitated, while $NaHCO_3$ gradually loses CO_2 and passes into Na_2CO_3.

According to KOVDA this kind of sodium carbonate formation and the transport of the products evolved by the above mentioned processes as well as of their geochemical distribution in waters, soils and subsoils represents the main source of sodium compounds capable of alkaline hydrolysis and plays a very important role in soil formation processes. The following ways of sodium carbonate formation development — partly or completely — are conditioned by these products.

2. According to HILGARD's theory [19]: by the action of NaCl or Na_2SO_4 on $CaCO_3$. HILGARD and many of his followers maintained in their time that this is the main way of sodium carbonate formation in soils. KOVDA [28] stipulates the conditions under which this way of sodium carbonate formation plays a decisive role.

3. GEDROITZ [14], 'SIGMOND [39], KELLEY [23] connect sodium carbonate formation with the fine structure of soils and with processes taking place in the colloid fraction according to the following well-known equations:

$$\text{abs. complex } 2\ Na^+ + H_2CO_3 = \text{abs. complex } 2\ H^+ + Na_2CO_3$$

or

$$\text{abs. complex } 2\ Na^+ + CaCO_3 = \text{abs. complex } Ca^{2+} + Na_2CO_3$$

(In case of CO_2 present)

In the opinion of numerous soil scientists this scheme represented the basic way of sodium carbonate formation in soil. It has to be realized, however, that it can be decisive or even important only under certain given conditions. GEDROITZ scheme is based on exchange reactions taking place in finely dispersed materials so sodium carbonate can be effectively formed in this way only in the presence of considerable amounts of colloid materials. In the investigation of this process the study of ion exchange processes, their states of equilibrium and reversibility is also very important because it explains why only a certain limited sodium carbonate concentration may be formed in the soil in this way. It follows from this that the above described way of sodium carbonate formation plays a significant role in soil formation processes only in places where the sodium carbonate concentration is not too high in the soil (for instance solonetz formation which is to be discussed later). It may be seen how wrong one would be to draw the conclusion that this is the only or the most important way of sodium carbonate formation because this compound often occurs in soils in such high amounts that cannot possibly be explained by the scheme of GEDROITZ. On the other hand, this scheme is very important when processes between the soil's colloid fraction and the soil solution are taking place in the presence of sodium salts. Naturally, in such cases the nature of the medium, the concentration of the solutions and the equilibrium reactions determine the tendency of soil formation and the intensity of soil forming processes. Therefore regardless of the way in which the greatest part of sodium compounds capable of alkaline hydrolysis has formed in the soil, regardless of how the finely dispersed materials being in equilibrium with the soil solution have formed, under certain conditions the processes determining soil formation leading to the development of particular salt affected soils may be correctly described by the above and other equations of GEDROITZ.

4. In literature the so-called "biological soda forming process" is also discussed by numerous authors. Sodium carbonate may be formed by the

biological reduction of sulphates in soil.

According to KOVDA [27], SZABOLCS [45], TIMÁR & SZABOLCS [52], VÁMOS [56], VERNER & ORLOVSKI [58], this way of sodium carbonate formation depends on certain conditions. The first and most important of these is that in the course of the process the reduction conditions must be continuously and permanently maintained. If oxidation took place then owing to the oxidation of sulphur containing materials the reaction of the soil would shift towards the acid pH range and not towards the alkaline, as was pointed out by KOVDA [27] and SZABOLCS [42, 43]. In addition to the effect of the reduction conditions, the quantity and quality of sulphur containing compounds present in the soil also influence biological sodium carbonate formation processes. According to TIMÁR [51] microbiological processes leading to sodium carbonate formation cannot take place above a certain concentration of water soluble sulphates in the soil.

This way of sodium carbonate formation is by no means common and decisive in salt affected soils, nevertheless in certain areas it does take place and it may be quite considerable. For instance it may occur and be significant under swampy bog conditions due to the effect of a slightly alkaline medium and dilute salt solutions, in the presence of organic matters of adequate quantity and quality which — according to TIMÁR and others — is also necessary to the development of these processes. In several alkali areas, for instance in the Baraba Plain and the Kulunda Plain in West Siberia, in the environment of lake Chad in Africa (CHEVERRY [8]) and — especially in the past — at some places on the Hungarian Plain considerable amounts of sodium carbonate have been formed by these processes.

5. Numerous authors claim that another biological way of the formation of sodium compounds capable of alkaline hydrolysis may be the decay of sodium containing plant materials. When discussing the possibility of sodium carbonate formation in steppes and desserts, KELLEY [23], KOVDA [27], BASILEVICH [5] described biological processes brought about by the growth and the decomposition of various plant materials.

As shown above, the various ways of sodium carbonate formation in soils are associated with certain conditions. It is evident that at one place one way, at another place another way of sodium carbonate formation may exert a decisive influence on soil forming processes. For example, if the salt concentration is relatively low in a soil where the percentage of the clay fraction is high, then the scheme of GEDROITZ represents the situation, while in the case of high electrolyte concentration in sandy soils that way of sodium carbonate formation has no importance. It must be pointed out that the role and significance of the various ways may alter in the same place as a consequence of changes in the local conditions. For instance in the 19th century on the Hungarian Plain water-logged conditions prevailed on far more extensive areas than now and the salinization and alkalinization processes intertwined with swamp and bog forming processes in the presence of large amounts of organic matter in the upper soil layers. At that time the importance of biological sodium carbonate formation brought about by reduction processes was much more considerable on those territories than today. In consequence of the

regulation of the river system and of soil amelioration, the extent of water-logged soils sharply decreased and a slow sinking of the water table took place. The formation of sodium carbonate on the soil surface ceased and now in most places such concentrations and dynamics of water soluble salts may be found in the soil profile that the reactions between the soil's colloid fraction and the soluble salts and the ensuing dynamics of sodium ions and soil colloids correspond mainly to the theory of GEDROITZ.

b) Formation of alkali soils under the influence of comparatively high concentration of sodium salts capable of alkaline hydrolysis

If the concentration of sodium carbonate affecting soil formation processes in the upper horizon of the soil profile is high, soils without structural B horizons develop. These soils display many similarities to saline soils formed under the influence of neutral sodium salts, for example they have no readily-distinguishable horizons separated by abrupt boundaries. On this basis in the Russian literature as well as in several other classification systems these soils are also named solonchak soils, that is, sodium carbonate solonchak to distinguish them from sulphate or chloride solonchaks developed due to the effect of neutral sodium salts. It is quite evident that, in spite of the similarities, these soils differ in many of their properties. The most important difference is that the soil reaction of sodium carbonate solonchaks is strongly alkaline while in the others it is near neutral. On the basis of this phenomenon 'SIGMOND [39] and KELLEY [23] equally included all of these soils in the group of alkali soils, but — according to the proposal of 'SIGMOND — they are referred to in the literature as saline-alkaline or alkaline-saline soils. RICHARDS [37] and BONNET [7] also adhered to this latter principle. Naturally this difference manifests itself also in the methods used for the amelioration and utilization of these soils.

Of the sodium salts capable of alkaline hydrolysis sodium carbonate plays the dominant role in this group of soils and, in all probability, the proportion of other salts is considerably lower than in certain other alkali soils to be discussed later. As KOVDA points out [28] geochemical processes may be responsible for this and on the basis of collodial examinations DARAB [50] arrived at the same conclusion.

Due to the effect of the strongly alkaline reaction of these soils, their colloid chemical properties, such as dispersity and swelling, and also some of their water regime properties differ from those of chloride or sulphate solonchaks.

KOVDA [25, 26] points out that while solonchak forming processes caused by neutral sodium salts may be observed mainly under natural conditions where salt accumulation from the ground water has but negligible importance or none at all, in most cases the formation of sodium carbonate solonchaks is closely connected with the mineralized ground waters and, in general, with more humid conditions. These statements of KOVDA — which are supported by the geochemical regularities of the geological circulation of materials recognized by KOVDA [26] as well as by VERNADSKY [57] and POLINOV [33, 34] — are also confirmed by the regularity of the distribution of sodium carbonate solonchaks in the various continents. For instance in West Siberia, Central and South-east Europe, in the Argentine and China

these soils have developed under the controlling influence of mineralized ground waters, under comparatively moderate climatic conditions.

As mentioned above, a comparatively high concentration of sodium compounds capable of alkaline hydrolysis is necessary for the formation of these soils. This limit concentration is, however, much lower than can be measured in the horizons of most Na-chloride or Na-sulphate solonchaks. On the basis of numerous examinations (KOVDA [25], SZABOLCS [41], SZABOLCS & DARAB [50], ANTIPOV-KARATAEV [2], GEDROITZ [14] it may be stated that this soil type, without structural B horizon, develops if the concentration of alkalinity expressed in sodium carbonate reaches 0.2 per cent or more in the upper soil horizons.

To demonstrate an example of the above discussed soil type, in the following I present the description of a structureless solonchak profile of the Danube valley:

Surroundings: Pasture of poor quality with bare spots.
Topography: Flat.
Vegetation: Lepidium cartilagineum, Camphorosma ovata, Atropis (Puccinellia) limosa, Nostoc commune.
Depth of the profile: 120 cm.
Effervescence with dilute acid: To the surface.
Alkalinity against phenolphtalein: To the surface.
Ground water table: 64 cm.
Genetic horizons:

A 0— 12 cm Grey (pale, mouse-grey, quite whitish when dry), moist, sandy silt. Undeveloped, weak structure. Relatively plentiful roots. Gradual boundary.

B_1 12— 30 cm Light grey, slightly moist, silty loam. Slightly prismatic structure (especially when dry). Gradual boundary.

B_2 30— 52 cm Whitish grey, loamy silt. Moist. Prismatic structure when dry. Horizon of lime accumulation. Abrupt boundary.

C 52—110 cm Grey, slightly silty sand. Wet. There are few, small gravels. Big, white, silty spots and grey, quite friable sandy spots. The silty spots get rarer with depth.

Soil type: Solonchak, on calcareous Danube alluvial sand.

Remark: In the description the A—B—C horizons are distinguished but — as may be seen from the description — this does not mean at all either that they have well developed structures or that the B-horizon is a structural one (which is to be discussed later). The A—B—C horizons were separated according to soil survey standards used in several countries (for instance in Hungary, USSR, etc.).

Figure 3 demonstrates the water soluble salt content of the 1:5 aqueous

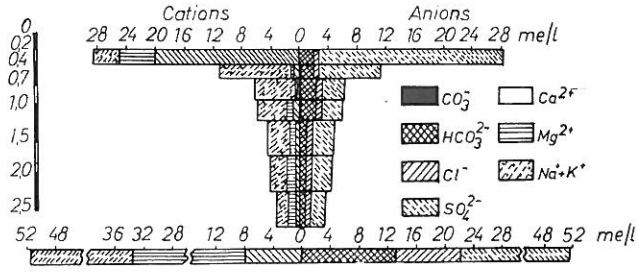


Fig. 3

Water soluble salt content of the 1 : 5 aqueous extract of a structureless solonchak soil (Danube valley)

extract of the above profile. It shows that the profile contains a considerable amount of sodium carbonate and sodium bicarbonate. Naturally other sodium salts are also present, especially at the soil surface. The ratio of total sodium salts to sodium salts capable of alkaline hydrolysis is higher at the surface than in deeper layers. An explanation for this phenomenon will be given later, in connection with the movements of various sodium salts in the soil profile. It is evident that — depending on the moisture conditions and on the tension of CO_2 in the soil's solid and liquid phases — Na_2CO_3 and $NaHCO_3$ may occur together in these soils, therefore it is always their total that must be taken into account.

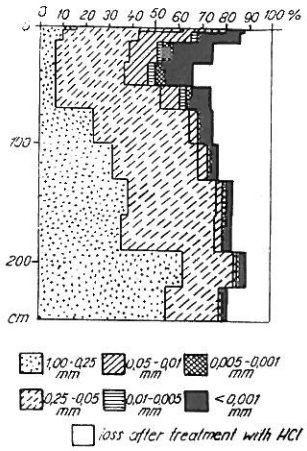


Fig. 4
Mechanical composition of a structureless solonchak soil (Danube valley)

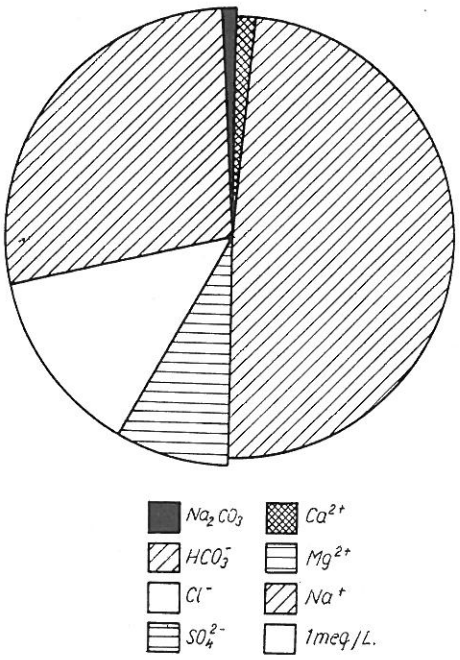


Fig. 5
Chemical composition of the ground water under a structureless solonchak soil (Danube valley)

Figure 4 presents the particle size composition of the same profile. It may be seen that the profile, especially in the upper layers, contains a remarkable amount of clay particles. The description of the profile indicated that the ground water is near the surface and exerts a permanent and intense influence on soil formation. Figure 5 demonstrates its chemical composition. This Figure supports the statements of KOVDA which assert that the formation and the chemical character of this soil type is profoundly influenced by the mineralized ground water. Apart from being mineralized to a large extent, this ground water has a remarkable alkalinity, another fact bearing out the theory of KOVDA relating to the sources of sodium carbonate formation in these soil types. On the basis of the above it may be stated that the total salt concentration and the concentration of sodium salts capable of alkaline hydrolysis of this soil are near the limit value above which alkali soils without structure develop.

c) Formation of alkali soils with structural B horizon under the influence of comparatively low concentrations of sodium compounds capable of alkaline hydrolysis

This group of alkali soils, having a so-called structural B horizon, is well-known. This horizon always has well-developed structure, mainly columns. It can be easily distinguished from the horizon above it which is less compact and the structure of which is less developed. This B horizon determines the genetic type of these soils, their main physical, chemical, physico-chemical and biological properties, as well as their fertility together with the possibilities of their agricultural utilization. These soils are called solonetz soils in the

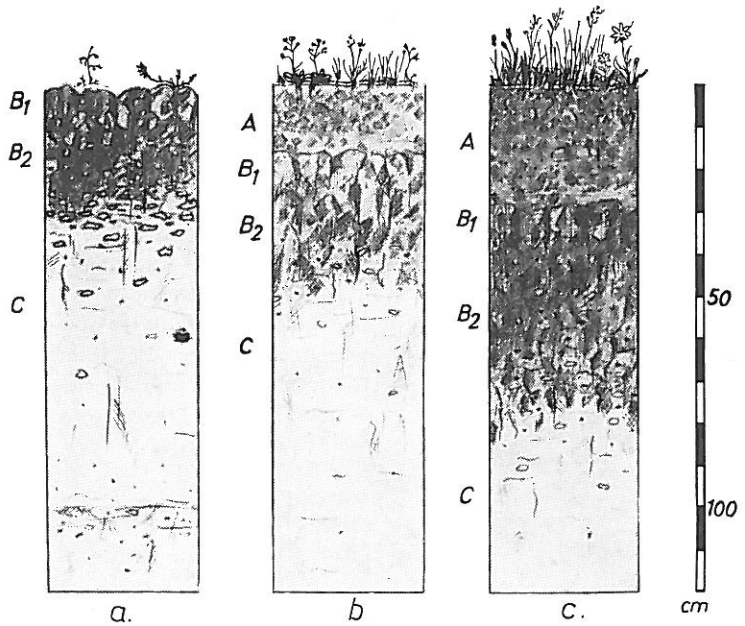


Fig. 6
Schematic profiles of alkali soils with structural B horizons

Russian literature and this denomination has been generally accepted. As regards their development, we may distinguish solonetz forming and solod forming processes. Solod formation will be discussed later.

Figure 6 demonstrates schematic profiles of alkali soils with structural B horizons. The structural B horizon is situated at various depths, depending on local circumstances. In some cases it is at the surface (the A horizon completely lacking).

The structural B horizon always markedly differs from the A horizon not only in morphology, colour and structure but also in its physical, chemical, physico-chemical and biological properties. Figure 7 schematically represents some of the chemical, physical and physico-chemical properties of a solonetz soil. (Adapted in modified form from KOVDA [25].) It demonstrates that at a given depth below the surface (in this case at about 30 cm) an illuvial horizon, that is, accumulation horizon may be found. This is named B or

B_1 horizon. In this horizon the accumulation of clay particles and sesquioxides may be observed and the water soluble organic matter content as well as the ESP value show their maxima, while the ratio of $SiO_2 : R_2O_3$ is the lowest there, signifying that the silicon compounds are comparatively in minimum quantity. On Figure 7 this horizon is between 20—30 cm, as is often the case in Nature, but it frequently occurs at depths other than this. Naturally in those cases the respective maximum and minimum values may be found at the depth where the B horizon developed.

It may be seen in Figure 7 that — as regards the movement and accumulation of materials — in the A horizon the situation is just the contrary. The A is the elluvial horizon according to Russian terminology.

Depending on local circumstances the solonetz soils have diverse characteristics and properties. Some of them have considerable amounts of water soluble sodium salts even in the upper layers (more than 4 millimhos) while others are practically devoid of those salts in their entire profiles. Of the water soluble sodium salts sometimes the bicarbonates, sometimes the sulphates or even the chlorides prevail. As regards the maximum accumulation of water soluble salts in the profile, as a rule, it is in the lower part of B_1 and the upper part of B_2 horizons but, depending on the conditions of formation, it may occur sometimes also in other layers, either above or below the B horizon. As regards the pH value of solonetz soils, it may also vary to a considerable degree. In some cases a strongly alkaline pH may be observed from the surface, sometimes the pH of the top layer is neutral or even slightly acid, and there are solonetz soils in the profiles of which strongly alkaline pH does not occur at all. In the B horizon, however, where the maximum exchangeable sodium percentage (ESP) may be found, the pH is always over 7 except in a few cases of strongly developed solods. In the B horizon the sodium ions are mainly in exchangeable form, absorbed by the soil colloids the maximum of which also occurs there. These exchangeable sodium ions — depending on the dynamics of the equilibrium conditions between the soil's solid and liquid phases — are capable of alkaline hydrolysis. This phenomenon is influenced by the quality and the quantity of colloids, by the CEC and ESP values, by the chemical composition and the concentration of the soil solution, especially its CO_2 tension, and by many other factors. In consequence of this phenomenon, the alkaline hydrolysis of the soil colloids saturated with sodium to a higher or lesser degree results in the more or less alkaline conditions of this horizon. It is evident that — with the exception of solonetz soils affected by strongly developed solod forming processes — in

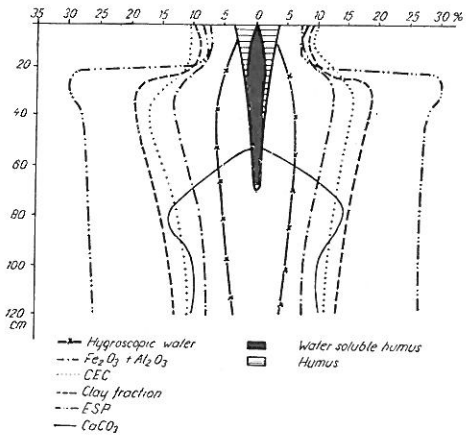


Fig. 7

Schematic representation of some of the physical, chemical and physico-chemical properties of a solonetz soil (after KOVDA, in a modified form)

the B horizon, where the sodium compounds capable of alkaline hydrolysis play the dominant role, the alkaline hydrolysis does take place as a rule, due to the interaction of the solid and liquid phases of the soil. For this reason the solonetz, as a type, must be included in that group of soils in which the tendency of soil forming processes is determined by sodium salts capable of alkaline hydrolysis. In this case the basic principles of the classification of 'SIGMOND and KELLEY must be accepted, just as the Subcommission on Salt Affected Soils of the International Society of Soil Science did in elaborating the schema of the World Map of Salt Affected Soils.

Naturally, as KELLEY [23], ARANY [4] and others point out, there are solonetz soils whose pH is definitely acid in the A horizon. But even in those cases the pH value of the B horizon is more than 7, as is obvious on the basis of the above described regularities of solonetz formation.

One of the indispensable conditions of solonetz formation is the action of comparatively dilute solutions of sodium salts. If the concentration of these salts is high, the processes take place as described in part b). Regardless of how these concentration conditions of sodium salts arise (the solutions may gradually become more and more saturated, or highly concentrated solutions may get diluted) they create one of the conditions of solonetz formation. Therefore one has to agree with GEDROITZ [14] who explained solonetz formation on the basis of dilute sodium salt solutions occurring during the leaching out of a solonchak. However, ANTIPOV-KARATAEV [2] and WILLIAMS [59] who explained it on the basis of sodium salt solutions becoming more and more saturated in the course of soil formation are equally right.

The presence of sodium salts in a certain concentration in the soil's liquid phase in itself does not necessarily result in the evolution of a solonetz profile. Another condition is that the salt solutions must migrate alternately upwards and downwards in the soil profile. This is how salt solutions of varying concentration communicate with the various soil layers in various periods, and in addition to this the soil layers involved become alternately drier or more humid; all these factors induce numerous essential, reversible and irreversible changes in the soil profile. These regularities have been observed by GLINKA [17], GEDROITZ [14], 'SIGMOND[39], TREITZ [53] and by many other experts who arrived at the conclusion that the periodical alternation of dry and humid conditions in the soil is necessary for the evolution of solonetz soils. During its up and down migration, the soil solution dissolves and accumulates certain products; in the case of repeated migrations the interaction between the solid and liquid phases of the soil always takes place under altered conditions. Thus these movements cause not only certain changes in the materials but they also result in the translocation of the various compounds within the profile.

On the basis of examinations conducted in the Hungarian Lowland, Figure 8 demonstrates how intensive the "season dynamics" (KOVDA [26]) of salt solutions is. It may be clearly seen in the Figure that in consequence of the changing natural conditions not only the concentration but also the chemical composition of the soil solution communicating with the various soil layers are altered during several months. It may also be seen in Figure 8 that, of the sodium salts capable of alkaline hydrolysis the carbonates are present in changing quantities and they migrate within the profile. This also proves that in solonetz soils, sodium carbonate is only one

of the sodium salts capable of alkaline hydrolysis, and it is in dynamic equilibrium with other compounds, especially with ones capable of alkaline hydrolysis. Naturally this equilibrium is determined by the quantitative and qualitative conditions of the solid and liquid phases of the soil at a given time. It must be mentioned that the examinations demonstrated in Figure 8 were conducted under irrigated conditions. Numerous observations have

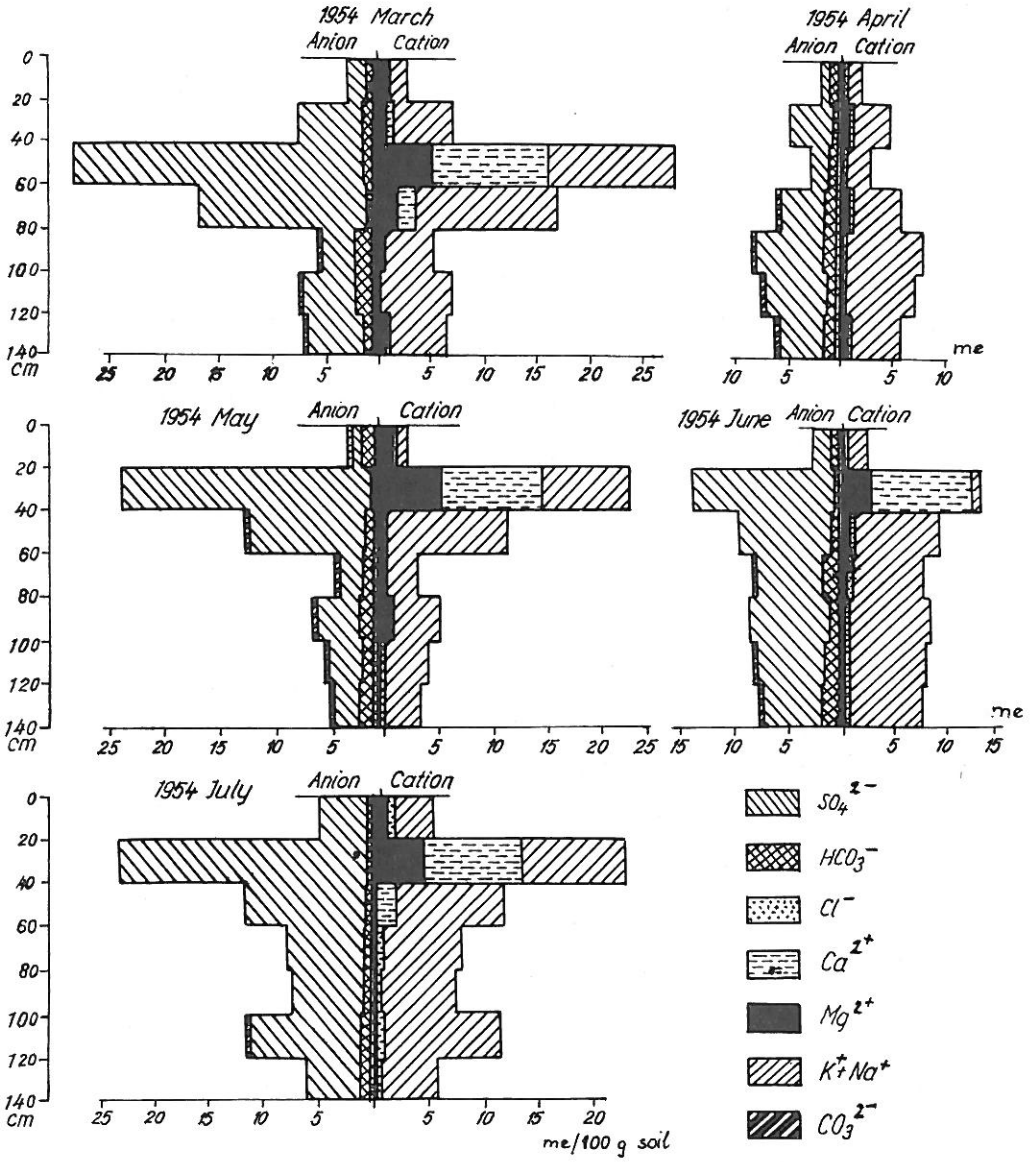


Fig. 8
Season dynamics of salt solutions (Szarvas, Hungary)

proved, however, that the migration of salts may be experienced also under non-irrigated conditions, in the case of solonetz formation, although of course then it is far less intensive.

Effected by the migration of relatively dilute sodium salt solutions, ion exchange processes take place and the soil colloids adsorb a certain amount of sodium ions according to the rules of equilibrium and ion exchange reactions. This phenomenon has been thoroughly studied by many experts and various equations have been formulated to characterize these processes. If the amount of sodium ions is expressed in percentage of CEC it makes it possible to determine certain limit values to describe the evolution of the solonetz profile particularly that of the characteristic B horizon. If the ESP value is over 5—7, then morphological signs of accumulation already manifest themselves in the B horizon. It becomes more compact and deteriorates in its water regime properties. At 20—25 ESP the columnar solonetz horizon, that is, the B horizon develops. It must be remarked that the ESP value must always be measured in the B horizon, because, as a rule, it is much lower in the A horizon.

Although in theory the various ion exchange processes are reversible, in shorter or longer periods they may induce irreversible processes in the soil. The processes which — in relation with soil colloids — are induced by the adsorption of sodium ions on soil colloids have not yet been satisfactorily studied. The investigations of GEDROITZ [14], JACKSON [20], GORBUNOV [18], GEREI [16] and others have revealed that the above mentioned ion exchange affects not only the surface of colloids but in all probability it also results in greater changes in the lattice layers of clay minerals and in the structure of the organo-mineral colloid compounds in the soil. The degree of these changes depends on the structure of the colloids, on the equilibrium conditions between the solid and liquid phases, on the pH of the medium and on many other factors. The joint effect of the above may bring about irreversible changes which are of decisive importance both in solonetz and solod formation.

Of these irreversible changes the turning into a mobile form and the migration within the profile of certain sesquioxides and silicon compounds are very important. It is in consequence of this migration that the differing properties of the A and B horizons — which are characteristic of solonetz formation — develop. This explains why — Figure 7 — the increase of silicon compounds and the decrease of sesquioxides may be observed in the A horizon, while in the B horizon the case is just the opposite. The migration of the clay fraction and of the water soluble organic matter displays similar tendencies.

Naturally these processes are profoundly influenced by the quantity and quality of the soil's clay fraction. In soils of coarse mechanical composition having no clay fraction solonetz formation usually does not occur. The above also explains why the ESP values indicating the commencement or the advanced stage of solonetz forming processes may markedly differ from the 5—7—20—25 limit values mentioned formerly in cases of different qualities and quantities of soil colloids.

During a shorter or longer period these processes may induce profound changes in the clay minerals of the soil, in their distribution and mineralogical character which remain unaffected even if the equilibrium conditions between the solid and liquid phases of the soil are altered and exhibit an opposite

tendency. For instance even if the concentration of the sodium salt solution considerably exceeds the limit values of solonetz formation, the soil having an already developed structural B horizon (characteristic of solonetzes) will not turn — or will do so only during a very long period, due to the effect of special conditions — into a salt affected soil without a structural B horizon. In cases like this the salt content may be very high in the upper soil layers, just as in the case of salt affected soils without structural B horizon, nevertheless the structural B horizon is present in the profile. (In the Russian literature these soils are often named solonchak-solonetz and soils referred to as saline-alkali in the literature of the English language also belong partly to this group.)

Similarly, the removal of sodium salt solutions of relatively low concentration which occasioned the formation of the solonetz structure will often leave the profile unchanged. Consequently the amelioration of solonetz soils is carried out in practice with amendments of strongly acid reaction (HCl, H_2SO_4) or with those capable of acid hydrolysis) [$Fe_2(SO_4)_3$, $Al_2(SO_4)_3$, and other acidic products]. One of the main effects of these compounds is that they induce ion exchange. They accomplish other changes, too, for example in the colloid structure.

In compliance with the above, according to the opinion of KOVDA [28], marked attention should be paid when soils of high NaCl and/or Na_2SO_4 content are leached out because then, if the soils have considerable colloid fractions, solonetz formation takes place as described by the schema of GEDROITZ. In order to hinder this process, KOVDA suggests the application of compounds capable of acid hydrolysis (for instance gypsum) parallel with the reduction of the sodium salt concentration, so that the amelioration of a solonchak may lead to the formation of a non-saline soil and not to that of a solonetz. In the absence of such materials, solonetz forming processes develop in soils having clay fractions, within a certain concentration range of sodium salts, regardless whether the concentration of these salts displays an increasing or decreasing tendency.

As regards sodium salts of relatively low concentration causing the formation of solonetz soils, essentially two cases may be distinguished:

1. The soil profile and the top layers are capillarily linked with the mineralized ground water.

KOVDA [25] states that in this case solonetz formation is intertwined with solonchak formation because sometimes (for instance if the water table rises) salt accumulation in the soil layers from the ground water may be of quite a large extent and then a solonchak soil develops. In these soils it is the fluctuation of the water table that determines the upward and downward migration of sodium salt solutions which is, as described earlier, one of the most important conditions of solonetz formation.

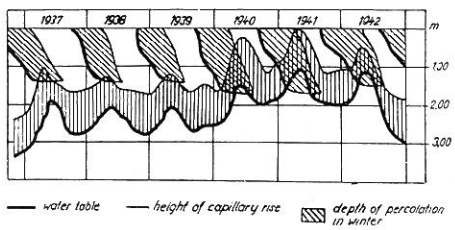


Fig. 9

The ground water and precipitation conditions in a solonetz area in Hortobágy (Hungary) in six years (after MADOS)

In the Russian literature this type of solonetz soils is named meadow solonetz, indicating that it is permanently affected by the ground water.

Naturally, apart from the ground water, precipitation also influences the migration of the solutions in the soil. Figure 9 demonstrates the ground water and precipitation conditions in a solonetz area of the Hungarian Lowland during a six-year period. It may be seen that in most years the precipitation water penetrating the soil meets the capillary ground water at certain times (MADOS [30]). The accumulation horizon of soluble salts may usually be found at the depth where the upward and downward movements of the solutions meet. KOVDA [26], ANTIPOV-KARATAEV [2], DARAB [9] and others point out that the distribution of the soluble salts' accumulation within the profile depends on whether the upward or downward solution movements are dominant. This is clearly indicated by the situation of the accumulation horizons of Na_2SO_4, $CaSO_4$ and $CaCO_3$ in the profiles.

To demonstrate an example of the above discussed soil type, in the following I present a description of a shallow meadow solonetz profile from the Hortobágy region of Hungary.

Surroundings: pasture of poor quality.
Topography: Slightly uneven, flat.
Vegetation: Artemisia monogyna, Polygonum aviculare, Festuca pseudovina.
Depth of the profile: 120 cm.
Effervescence with dilute acid: 32 cm.
Thickness of humus layer: 56 cm.
Alkalinity against phenolphtalein: 50 cm.
Ground water table: 230 cm.
Genetic horizons:

A	0— 3 cm	Pale grey, moist, weak, many fine roots, ash-like feel solodized sandy loam. Abrupt boundary.
B_1	3— 15 cm	Grey, dry, extremely hard, distinctly columnar structure, clay loam. Roots relatively plentiful. Tops of columns, and at some places the sides, are discoloured, solodized. Abrupt boundary.
B_2	15— 31 cm	Grey, somewhat darker, moist, slightly hard, fine prismatic structure, clay loam. Moderate roots. In $CaCO_3$ abrupt, otherwise gradual boundary.
B_3	31— 55 cm	Brownish grey, somewhat lighter in colour, moist, slightly hard, fine prismatic structure, clay loam. Few roots. Iron mottles and iron concretions growing more frequent with depth. White lime spots, fine lime concretions. Abrupt boundary in colour.
C_1	55— 93 cm	Greyish yellow, moist, moderate hard, coarse prismatic structure, loess-like clay loam. Dark, clayey humus streaks, white lime mottles, a lot of lime concretions. Stains of iron, soft iron concretions. Gradual boundary.
C_2	93—110 cm	Greyish yellow, moist, moderately hard, loess-like clay loam. Lime and iron concretions, rusty stains of iron. Greenish grey mottles of gley.
	110—130 cm	Yellow loamy clay, lots of lime and iron concretions.
	130—150 cm	Yellow silty clay, lime and iron concretions.
	150—180 cm	Yellowish grey clay, segregated lime and lots of iron concretions.
	180—210 cm	Grey clay. Some segregated lime and iron. Gley formation.
	210—220 cm	Reddish brown, sticky clay.

Soil type: Shallow meadow solonetz on calcareous loess-like clay loam.

Figure 10 demonstrates the water soluble salt content in the 1 : 5 aqueous extract of this profile developed under the influence of the processes described above. In Figure 11 the composition of the ground water is represented. The close relationship between the chemical composition of the soil profile and the ground water is quite obvious. The sodium carbonate content is considerable both in the soil and in the ground water although — as is

often the case in sodium carbonate containing solonetz soils — it appears only at a depth of about 25 cm in the profile. It must be added that the depth of the appearance of sodium carbonate may change within the same profile depending on the seasonal dynamics of the soluble salts.

In most of these soils the B horizon is situated near the surface, consequently the A horizon is relatively shallow, or, in certain cases, where the B horizon is at the surface, it is completely missing.

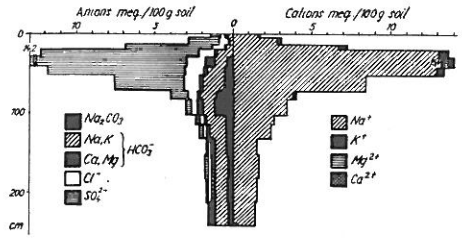


Fig. 10

Water soluble salt content of the 1 : 5 aqueous extract of a shallow meadow solonetz soil (Hortobágy, Hungary)

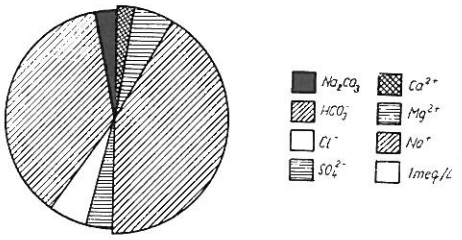


Fig. 11

Chemical composition of the ground water under a shallow meadow solonetz soil (Hortobágy, Hungary)

The great majority of sodium carbonate containing solonetz soils have developed through the above described processes, under the influence of mineralized ground waters. They often occur on territories where the climatic conditions are far from being arid, for instance in the Argentine, Canada, Victoria (Australia), Hungarian Lowland etc.

Naturally these soils — besides the frequent occurrence of sodium carbonate or in some cases in its absence — reflect the geochemical characteristics of the given areas, especially the chemical composition of the ground waters. They are often rich in sodium sulphate (for instance in Alberta [Canada] the Hungarian Lowland etc.).

In the B horizons of these soils the quantity of the exchangeable sodium ions is relatively high but in certain cases — due to special equilibrium conditions between the soil's liquid and solid phases (for example the ground water is but slightly mineralized, the downward movements of the soil solution are dominant and intensive) — the columnar structure does not develop. In a soil like that a B horizon displaying a relatively limited accumulation of soluble salts may be found. In the USSR, Canada, Hungary etc. these soils are named solonetzic or solonetz-like soils.

With regard to the amelioration of solonetz soils developed under the influence of mineralized ground waters, the first step must be the lowering of the water table to cut off the communication of ground water with the upper layers of the soil profile. Even if this is achieved, the tendency of the subsequent soil formation processes may differ in various cases. For instance they may be conducive to solod formation.

2. In another group of solonetz soils the mineralized ground water is at such a great depth (more than 6—8—10 meters) that it exerts practically no influence on soil formation processes. The sodium salt solutions effecting solonetz forming processes get into the soil profile from other sources in another way. Under arid or semiarid conditions, the weathering of minerals

and the decomposition of organic and inorganic compounds or the transport of water soluble salts by the surface waters may constitute such sources. Depending mainly on the climatic conditions the repeated downward and upward migrations of the sodium salt solutions form the profiles of these soils which — although they have all the features characteristic of solonetzes — noticeably differ from those developed under the influence of ground waters.

Figure 12 shows (KOVDA [25]) the salt profile of this soil, named steppe solonetz in the Russian literature. It is common in the Ukrainian SSR, in the Trans-Volga region, in Kazakh SSR, in China, Australia and in many places in semiarid countries.

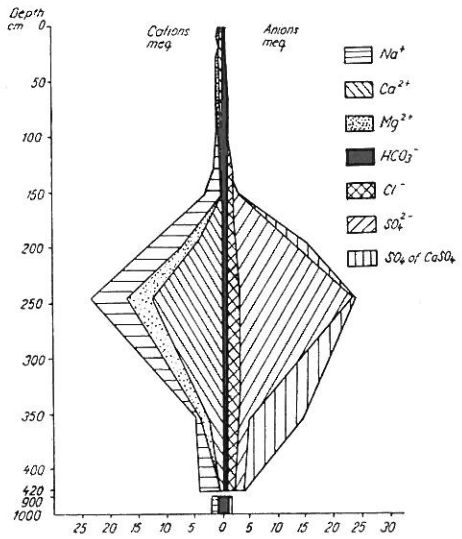


Fig. 12
Salt profile of a steppe solonetz soil (after KOVDA)

In steppe solonetz soils, the accumulation of water soluble salts may often be found deeper than in meadow solonetz soils. In frequent cases this is true also of the B horizon, consequently the A horizon is much thicker. Naturally the B horizons of these soils display alkaline reaction — thus they may be considered as media capable of alkaline hydrolysis — but usually free sodium carbonate cannot be found in the upper layers or even in the whole profile and sometimes the amount of sodium bicarbonate is low as compared to that of sodium sulphate or, perhaps, sodium chloride. According to the statements of KOVDA [26] and POLINOV [33, 34] relating to geochemistry, the more arid the conditions are under which these soils develop, the higher is the ratio of chlorides to sulphates in the water soluble sodium salts. Naturally this regularity, though true in the general sense, may be significantly influenced by local conditions. It must also be noted that solonetz soils of high sodium carbonate content may develop also under these climatic conditions if the parent material contains considerable amounts soluble carbonates.

As regards the amelioration of these soils, the main tasks are to improve the properties of the soil horizons and to alter the dynamics of salts within the profile. If proper leaching is assured, the application of amendments capable of acid hydrolysis is very effective on these soils and the loosening of the B horizon is often also advantageous (ANTIPOV-KARATAEV [2]).

Solod forming process

The solod forming process is one of the particular processes of salt affected soil genetics leading to the formation of the solod type of salt affected soils but — in spite of the numerous publications discussing this subject — it has not been thoroughly studied and elucidated.

In the literature the following schema of solod formation (GEDROITZ [14]) has been generally accepted:

solonchak → solonetz → solod

According to this schema this process develops parallel with the leaching out of solonchaks, under the influence of diluted, slightly alkaline solutions (or even water in the last stages of the process).

Although the above schema seems to be quite simple, the processes taking place in the course of solodization are by no means simple. The sodium saturation of the soil colloids decreases. At the same time, the H ions also assume an important role. Owing to the alternating occurrence of these processes — which are more intensive than in the case of solonetz formation —, the lattic layers of clay minerals are loosened, altered and sometimes even destroyed. The complex organo-mineral compounds are also decomposed in the course of solod formation. In consequence of the above the accumulation of silicon compounds may be observed on the soil surface and/or in the upper layers of the solod profile. This phenomenon was observed first — even before GEDROITZ — by POPOV [35] in the forest steppe belt in the European part of the USSR.

Solod forming processes commonly occur in the salt affected soils of Central and South-east Europe, both in the European and Asiatic parts of the USSR, in China, Canada, USA, South America, Australia etc. As regards the genetics of solod soils, scientists are of conflicting opinions which probably may be explained by the diversity of solod soils and of solod forming processes.

As already mentioned, considerable amounts of silicon compounds accumulate on the soil surface and/or in the upper soil horizons during solod forming processes. As regards the chemical composition of these silicon compounds, GEDROITZ named them "amorphous silicic acid". Several experts (MURAKÖZY [32], TYURIN [54], WILLIAMS [59], BOLISEV [6] and YARKOV [60]) explain this accumulation mainly by biological factors. Others (KOVDA [24], BAZILEVICH [5] and SZABOLCS & DARAB [47]) have detected relations between the high silicon content of these soils and that of the ash of plants grown on them, and suggest the particular biological cycle of silicon compounds as one of the possible causes of the formation of solod soils. KOVDA notes that silicon compounds in the ground water often play a prominent role in solod formation. GORBUNOV [18] and GEREI [16] point out that the accumulated silicon compounds contain a considerable amount of finely dispersed quartz in solod soils.

The accumulated silicon compounds are still determined by the method of GEDROITZ, in 5 per cent KOH. Their quantity extracted by this method may amount to 1 per cent or even more (referred to the total weight of the soil) in the upper layer of a solod soil. From the 5 per cent KOH extract of the soil the ratio of silica to sesquioxides can also be determined by GEDROITZ' method. If the SiO_2/Al_2O_3 ratio is higher than 2 it indicates solod formation.

As several critical comments relating to the above statement of GEDROITZ may be found in the literature, it should be remarked that

1, Silicon compounds accumulated in solod soils probably consist of several types of both biological and non-biological origin.

2, Silicon compounds are not only formed in the course of solodization but they are also moving both on the soil surface and in the profile. For instance, as a rule, the most characteristic solod spots develop in microdepressions. In cases like these the increased accumulation of silicon compounds on the surface is fairly evident because they are transported there from the surrounding places.

The above explains also why it is possible that the amount of SiO_2 extracted with 5 per cent KOH and the SiO_2/Al_2O_3 ratio (both determined with GEDROITZ' method) do not always correspond to morphological observations indicating the occurrence of solod forming processes in a given place.

As regards the morphology of a solod profile, two cases should be distinguished, as may be seen in Figure 13. Figure 13a represents a schematic solod profile, when the accumulation of SiO_2 is on the surface. In this case the A horizon is the solodized one. This occurs, as a rule, if the ground water is capillarily linked with the upper layers of the soil profile or if a shallow solonetz has been solodized. Due to this fact, parallel with solod formation, a relatively high ESP value may also be measured in the A horizon and the pH is often alkaline. Therefore the statements implying that the solodized horizon of a solod soil displays acid reaction cannot always be verified.

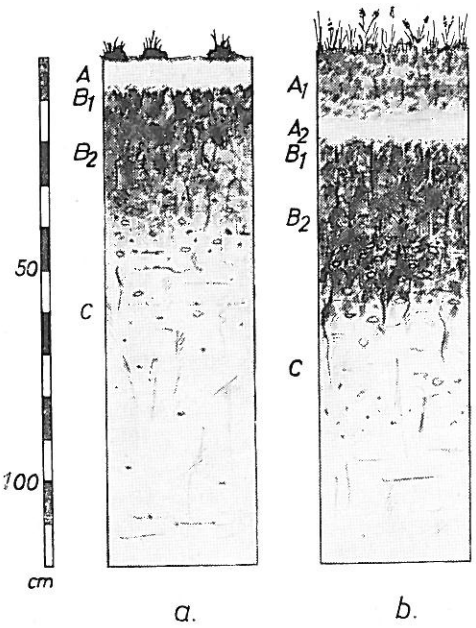


Fig. 13
Schematic profiles of solod soils

Solod forming processes occur only if waterlogged and/or water saturated conditions regularly alternate with drying up in the horizons involved, as is commonly the case in microdepressions.

Solod formation represented in Figure 13a occurs usually in heavy textured soils where, as a result of the slowness of solution movements, water saturated conditions are prolonged.

The B horizon is also often solodized and — unlike the well-developed solonetz soils — the columns or crusts of this horizon contain a considerable amount of silicon compounds and are lighter in colour.

The accumulation of sesquioxides can always be observed under the solodized horizon and, as with solonetz soils, the clay content is always higher there than in the A horizon.

Under the influence of mineralized ground water, if it is linked capillarily with the upper soil layers, the solod profile may become salinized and it happens sometimes that solonchak forming, solonetz forming and solod forming processes — which are separated in the schema of GEDROITZ — are intertwined in the same profile (SZABOLCS & MÁTÉ [46], SZABOLCS [40, 43]).

This type of solod soil is fairly common in Western Siberia, in the Hungarian Plain and in many other places where the alkaline ground water is linked with the soil profile. The following description of a solod profile from the Hortobágy region (Hungary) is presented:

Effervescence with dilute acid: 36 cm.
Genetic horizons:

A 0—12 cm Light grey, heavy clayey loam. Finely granulated structure, laminated in some places. A large amount of dry, decayed roots. Clear boundary.

B_1 13—40 cm More compact that the A horizon heavy, clayey loam. Dark coloured, columnar, prismatic structure. The upper parts of the columns are covered with grey dust observable sometimes also in the prisms. The upper boundary surface of the columns is blurred. Further downwards they are of an intensive black colour. Slightly damp residues of roots. Gradual boundary.

B_2 41—68 cm Brownish black, downwards the colour gets lighter. Slightly moist, heavy, loamy clay. On drying it assumes a nutlike structure. Few decayed roots. Iron concretions from pea to nut-size, alternating with gley patches. Gradual boundary.

C 69— cm Yellow, loess-like, structureless clay with gley and rusty layers.

Table 1

Analytical data of 5% KOH extract of a solod soil from Hortobágy (Hungary)

Horizon (depth in cm)	SiO_2 soluble in 5% KOH	Al_2O_3 soluble in 5% KOH	$SiO_2 : Al_2O_3$ ratio in eq.	pH	
				H_2O	KCl
A 2—10	3.96	0.260	13.0	6.9	6.1
B 16—24	2.40	0.272	7.2	8.0	7.1

In Table 1 the analytical data of the 5 per cent KOH extract of the above profile and the pH values are presented.

In Figure 13b the schematic profile represents a soil where solod formation manifests itself in the A_2 horizon. In cases like this the A_1 horizon is humous, while under the solodized A_2 horizon displaying the maximum $SiO_2 : Al_2O_3$ ratio the B horizon is also affected by solod forming processes to a greater or lesser degree.

As a rule, this type develops where the ground water is but rarely or not at all linked with the upper soil layers. Consequently the downward movements of the soil solution can be more intense than in the former type. This is why the A_1 and A_2 horizons of solod soils developed in this way have acid pH and the profile does not contain a considerable amount of water soluble salts. The ESP values are comparatively low or even negligible in the A_1 and A_2 horizons and often also in the B horizon.

This type is characteristic of the forest steppe and steppe areas of the Russian Plain, Australia etc.

The solod forming process is closely related to solonetz forming processes and the occurrence of soils of the pure solod type is far rarer than that of slightly or strongly solodized solonetzes (for instance in the Hungarian Plain, in Canada, Australia etc.) or solonetzic solods, depending on which process is dominant and more developed.

In the case of solod soils or solonetz soils, especially when the profile is linked with the ground water, sometimes a high amount of exchangeable Mg may be found in the B horizon. (SZABOLCS [43] and MÁTÉ [31]). The role of Mg in the formation of salt affected soils has not been studied satisfactorily,

and — in spite of the numerous publications on this subject — its nature still is not clear enough.

KREYBIG [29], ANTIPOV-KARATAEV [3], ARANY [4], and others described salt affected soils containing high amounts of water soluble or exchangeable Mg. Various theories have been advanced to explain the formation of these so-called magnesium soils but the lack of systematic studies and sufficient available data have prevented the thorough elucidation of these processes and the adequate grouping of these soils within the salt affected soils.

ELGABALY [11], KOVDA [28] and GEREI [15] point out that the accumulation of magnesium ions is connected with the transformation of soil colloids — especially clay minerals — in the course of solod- and certain solonetz forming processes, for instance with montmorillonite formation. When discussing solonetz and solod formation, ELGABALY calls attention to the consequences of the simultaneous occurrence of sodium and magnesium ions in the course of the evolution of salt affected soils.

Solod forming processes often occur also under irrigated conditions especially in areas where the migration of slightly alkaline solutions within the profile of heavy textured soils is intense and temporary water-logged conditions prevail (for instance in the case of rice growing (SZABOLCS & DARAB [47]). Thus the conclusion may be drawn that both secondary salinization (secondary formation of solonchak soils), secondary alkalinization (secondary formation of solonetz soils) and secondary solodization (degradation of irrigated soils) are frequent under irrigated conditions (SZABOLCS [43]) but discussing the details of these processes is beyond the scope of this paper.

Some particular physical, physico-chemical and chemical effects of sodium carbonate on soil properties

It is evident from the foregoing that sodium salts — particularly those capable of alkaline hydrolysis — exercise a decisive influence on soil forming processes. It is also evident that in the presence of the latter ones sodium ions play a dominant role in ion exchange reactions because the sodium ions, as compared with the ions of calcium and magnesium, will be adsorbed by the soil colloids more intensively in alkaline medium than in a neutral one. This fact exerts a profound effect on the dynamics of soil forming processes which will differ depending on whether neutral sodium salts or those capable of alkaline hydrolysis prevail in the soil.

These questions are discussed in detail in the literature (SZABOLCS & DARAB [50], ANTIPOV-KARATAEV [2], KOVDA [26], GEDROITZ [14], KELLEY [22] etc.) therefore in the following I would like to illustrate, with a few examples only, the differences in the physical, physico-chemical and chemical properties of soils affected by neutral sodium salts or by salts capable of alkaline hydrolysis.

In the course of investigations on the movements of solutions within the soil profile, in most cases relatively little attention was paid to the chemical composition of the migrating solutions, although it plays a very important role in the development of salt affected soils unless the solutions are very dilute if distilled water is involved.

In order to elucidate this question, experiments were conducted with soil columns and solutions of various chemical composition in our laboratory [49] with the following methods:

One meter high plastic tubes, 12 cm in diameter, were filled with chernozem soil containing only a negligible amount of water soluble salts and displaying no signs of alkalinization. In the plastic tubes there were holes with taps, one in every 10 cm, and in the course of the experiments samples were taken from the tubes at different intervals in order to subject them to further analyses. The soils were treated with the following solutions, respectively (the concentration of the solutions was 0.1 N):

1, H_2O
2, NaCl
3, Na_2SO_4
4, Na_2CO_3
5, $MgCl_2$
6, $Na_2CO_3 + Na_2SO_4 + NaCl$
7, $Na_2CO_3 + Na_2SO_4$
8, $NaCl + Na_2SO_4$

To assure the capillary movements of the solutions the treatments were executed by pouring the solutions into pots in which the tubes stood.

First of all it was observed that the different solutions did not rise at the same speed. It took the water 11 days, $MgCl_2$ 11 days, NaCl 15 days, and Na_2SO_4 18 days to reach a height of 1 meter. During the first 18 days the Na_2CO_3 solution rose 1.6 cm daily on the average, but later on no further noticeable rise could be observed. It seems very probable on the basis of this observation that the colloid-chemical processes taking place in the soil layers (the soils' getting peptized and dispersed to a great extent) due to the effect of Na_2CO_3, which is capable of alkaline hydrolysis, prevented a rapid rise of the solution.

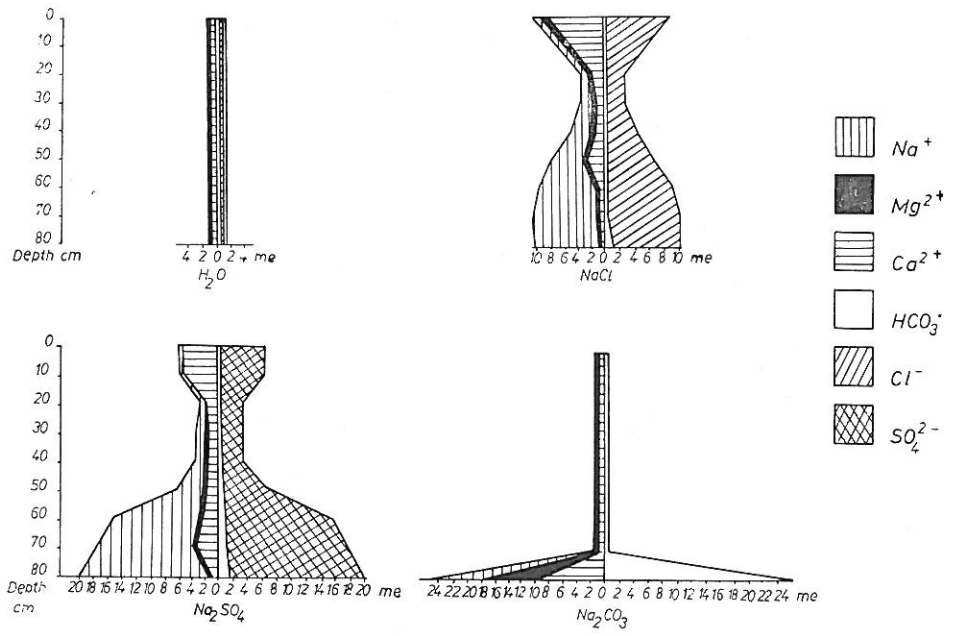


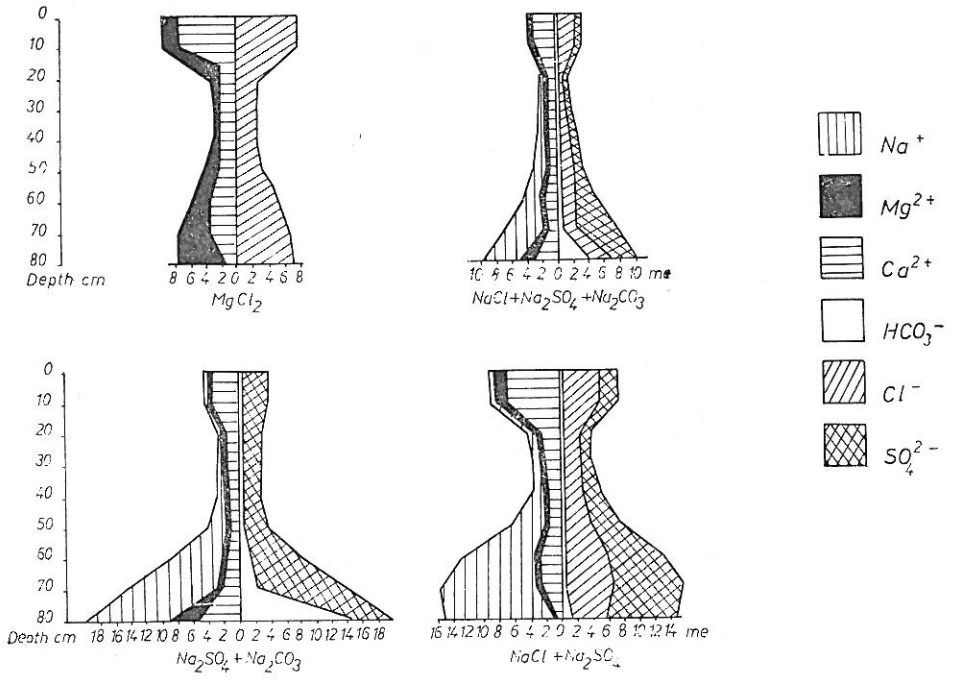
Fig. The effect of different salt solutions

At the end of the experiment we determined the salt profiles of the soil columns (Fig. 14).

Figure 14 clearly demonstrates the significant changes, depending on the quality of the given salt solution, that were observed in the salt profiles of the soils and it also gives a good explanation concerning the above described properties of sodium carbonate.

When a soil column is treated with a sodium chloride solution, the maximal amount of chlorides accumulated in the top layers of the soil column. Their amount was less in the middle part of the profile but it increased again in the lower layers. The data show that in the upper horizons the chloride ions appeared mainly with the cations of alkali earth metals, while in the middle and lower horizons they appeared with the cations of alkali metals. From the localization of the $CaCl_2$ and $MgCl_2$ maximums in the upper part of the soil profile, the conclusion can be drawn that these salt solutions moved faster in the soil than the NaCl solution. It may be assumed that the first portions of the NaCl solution into enter correlation with the adsorption complex of the lower soil layers. Owing to this it was not a pure NaCl solution that moved towards the upper layers in the soil column but a mixture of NaCl + $MgCl_2$ + + $CaCl_2$. The higher the solution got in the soil column, the more $CaCl_2$ and $MgCl_2$ it contained. These formed as a result of exchange reactions. The total alkalinity of the lower part of the soil column increased to value even higher than 1 me.

In the soil columns treated with a Na_2SO_4 solution, as in the case of the NaCl solution, the salts rose to the surface. The distribution in depth, here too,



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on the salt profiles of soil columns

Table 2

Microaggregate analysis of a chernozem soil subjected to various treatments

Treatment	Depth of soil sample	Hygroscopic water in %	Fraction in per cent					
			1—0.25	0.25—0.05	0.05—0.01	0.01—0.005	0.005—0.001	<0.001
			mm					
$Na_2CO_3 + Na_2SO_4$	0—10	2.96	3.62	32.03	41.21	6.90	12.81	3.43
	10—20	2.91	3.26	29.97	45.16	7.72	11.08	2.81
	20—30	3.22	3.26	32.07	43.01	8.27	9.60	3.79
	30—40	2.58	2.75	29.99	43.55	7.74	13.88	2.09
	40—50	2.42	3.27	29.09	44.05	9.53	10.68	3.38
	50—60	2.62	3.10	31.21	42.12	8.69	12.11	2.77
	60—70	2.34	3.67	26.82	42.43	9.18	13.71	4.19
	70—80	2.28	2.64	25.33	37.08	9.24	18.35	7.36
	80—90	2.13	3.05	25.12	34.61	8.83	17.89	10.50
$NaCl + Na_2SO_4$	0—10	2.80	3.27	28.83	44.82	9.31	10.54	3.23
	10—20	2.47	3.01	31.87	42.61	9.80	9.77	2.94
	20—30	2.41	3.33	31.89	44.24	6.72	10.92	2.90
	30—40	2.54	3.57	30.78	44.35	8.23	10.08	3.01
	40—50	2.23	2.87	30.79	43.38	8.00	11.79	3.37
	50—60	2.30	3.22	28.95	43.14	9.82	11.33	3.54
	60—70	2.23	1.66	27.32	43.30	10.00	14.12	3.60
	70—80	2.45	3.04	26.58	39.04	8.82	17.66	4.86
	80—90	2.22	3.41	26.50	35.18	8.76	16.65	9.50
$MgCl_2 + Na_2SO_4$	0—10	2.35	3.43	32.64	41.59	9.99	9.86	2.49
	10—20	2.36	3.32	31.34	41.58	9.98	10.20	3.58
	20—30	2.34	3.08	30.66	43.40	8.67	11.09	3.10
	30—40	2.36	3.83	31.28	41.22	9.45	10.81	3.41
	40—50	2.32	3.28	31.48	41.13	7.67	13.17	3.27
	50—60	2.49	2.77	29.19	44.84	11.69	8.09	3.42
	60—70	2.35	3.03	28.68	40.83	11.02	12.59	3.85
	70—80	2.53	4.12	26.27	40.84	11.75	13.06	3.96
$Na_2CO_3 + Na_2SO_4 + NaCl$	0—10	2.29	3.19	30.07	43.55	9.31	10.75	3.13
	10—20	2.26	3.15	31.48	42.32	8.67	11.48	2.90
	20—30	2.32	3.41	30.01	40.31	10.90	12.27	3.10
	30—40	2.33	3.15	29.54	43.37	8.94	11.56	3.44
	40—50	2.15	3.62	29.83	42.17	9.22	11.70	3.46
	50—60	2.33	2.93	29.67	41.51	9.95	11.69	4.25
	60—70	2.12	2.99	26.93	37.82	8.61	17.53	6.12
	70—80	2.21	2.91	25.03	35.51	8.12	16.85	11.58

varies. The largest quantities of sulphate were found at a depth of 60—70 cm where they were bound mainly to sodium ions. The distribution of water soluble Ca and Mg compounds was more or less uniform. These data also show that sulphates moved somewhat slower in the profiles than chlorides.

In full conformity with the preceeding case, however, in the lowest horizons of the soil column, cation exchange, due to the infiltration of sodium ions, caused alkalinization to take place.

The drawing in Fig. 14 representing the effect of Na_2CO_3 is different from the two above described profiles. Here, as a consequence of the process described above, the signs of salt accumulation began to manifest themselves at depth of about 70 cm. This held particularly true for salts capable of

alkaline hydrolysis. Above this level, the salt profile demonstrates that the total quantity of salts was minimal and that the whole profile, 70 cm and above, resembled more a chernozem without any alkalinization than the salt profiles described above. Naturally, in the soil layers lying lower than 70 cm the colloid-chemical effect of sodium ions and the formation of an impermeable layer in the alkaline media hindered the further movement of the salt. This figure shows the very different conditions we have to face if salts capable of alkaline hydrolysis instead of neutral sodium salts move about in soils. The adsorption of Na ions by soil colloids and alkalinization may occur even in the latter case but the sodium ions are bound to the soil particles much more intensely in an alkaline medium. In the soil layers where this takes place to a great extent, the physical and physico-chemical soil properties change so considerably that it exerts great influence on further soil formation processes, and on the soil's agronomical properties.

It can also be seen in Figure 14 that if not the single salts but their mixtures are involved and if the mixtures contain sodium carbonate, its considerable effect on the movements of solutions is manifested in each case. Thus, when neutral sodium salts and those capable of alkaline hydrolysis were applied together, the salt accumulation was more intense in the upper horizons of the soil column than when only sodium carbonate was used but at the same time it was less than when only neutral sodium salts or their mixtures were applied.

During the experiments, in addition to the distribution of the salt profiles, the soils' physical characteristics observable in different horizons due to the effect of various treatments were also studied. We examined the microaggregate composition of the soils. The obtained data are presented in Table 2.

It can be seen in Table 2 that in each case where sodium carbonate was used in the treatments, the apparent amount of the clay fraction was significantly larger in the lower soil layers, as compared to the values measured in the case of the application of neutral sodium salts.

To compare the results of the microaggregate analyses and mechanical analyses, the dispersity factors recommended by KACHINSKY [21] were determined for the soils in question.

According to KACHINSKY, the dispersity factor may be characterized by the following equation:

$$\% \, K = \frac{100 \cdot a}{b}$$

K = KACHINSKY's factor
a = clay fraction determined in the course of microaggregate analysis
b = clay fraction determined in the course of mechanical analysis.

The results of these examinations are presented in Figure 15. It can be clearly seen in this figure that the dispersity factor was hardly changed by the effect of $MgCl_2$ solution as compared with the control; NaCl and Na_2SO_4 induced gradually larger changes, while the soda solution caused the dispersity factor to increase significantly. The transitional cases of the same tendencies may be observed if mixtures of certain salt solutions were used. This figure clearly shows also that the dispersity factors reached their highest value in

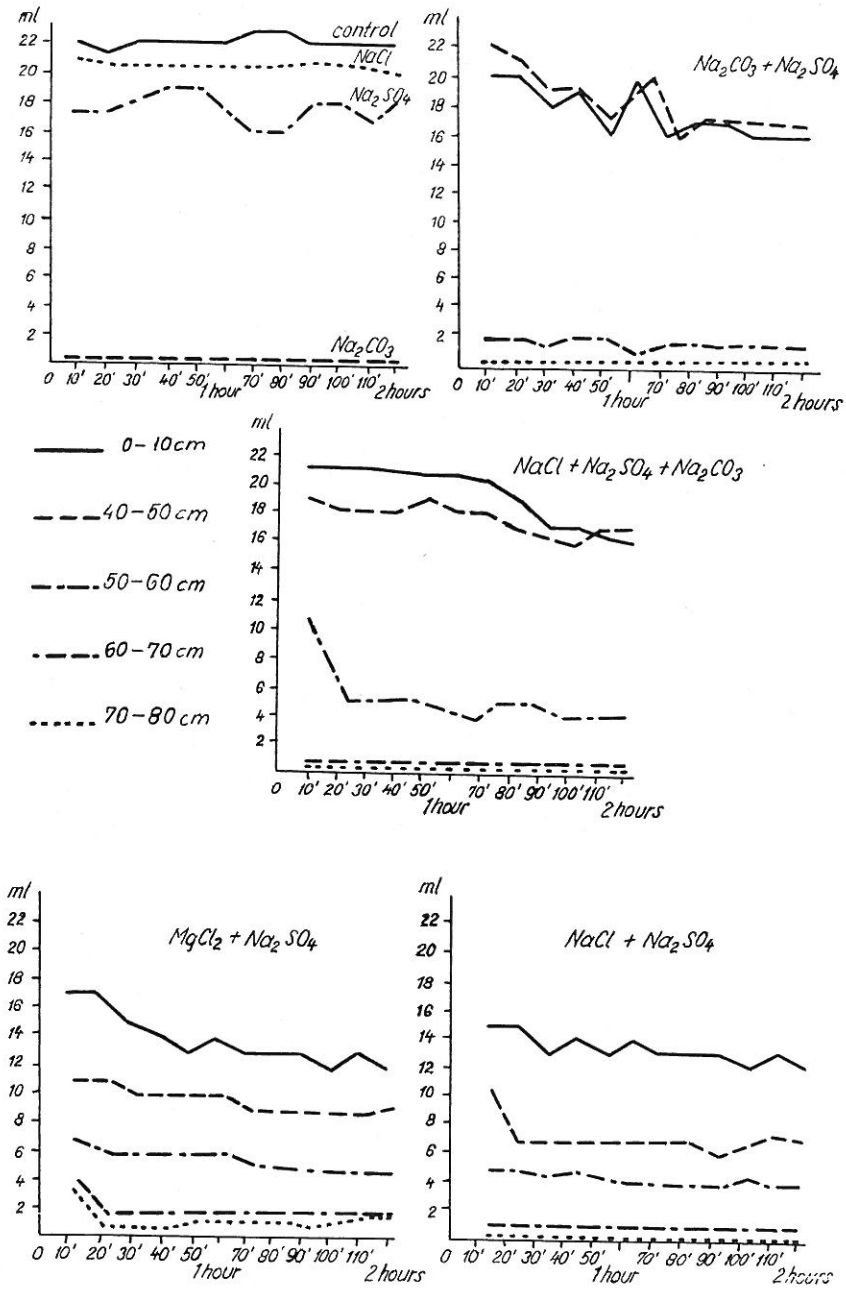

Fig. 15
Water permeability of soils treated with different salt solutions

the lowest horizons, where the effect of the solutions of sodium salts was most intense. It is interesting to observe that $MgCl_2$ did not induce significant changes even in this horizon. In the lowest horizons the increase of the dispersity factor was twice as high due to the effect of the soda solution as due to that of the sodium sulphate solution, which was the next most intense. The structure factor of VAGELER was also determined. This factor, suggested by VAGELER [55], is characteristic of the possibilities of the soil structure formation and is in direct proportion with the water stability of the microaggregates.

$$C = \frac{(a - b)\,100}{b}$$

C = VAGELER's factor
a = the amount of the irreversible microaggregates on the basis of the mechanical analysis
b = the amount of the irreversible microaggregates on the basis of the microaggregate analysis.

The results of these analyses presented in Figure 16 are in full accordance with the results of analyses shown in Figure 15.

It can be clearly seen in this figure that the values of VAGELER's structure

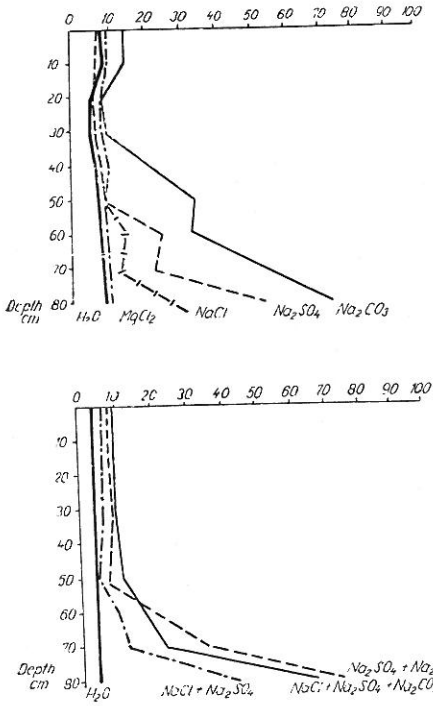

Fig. 16

The dispersity factor of KACHINSKY in the soils treated with different salt solutions

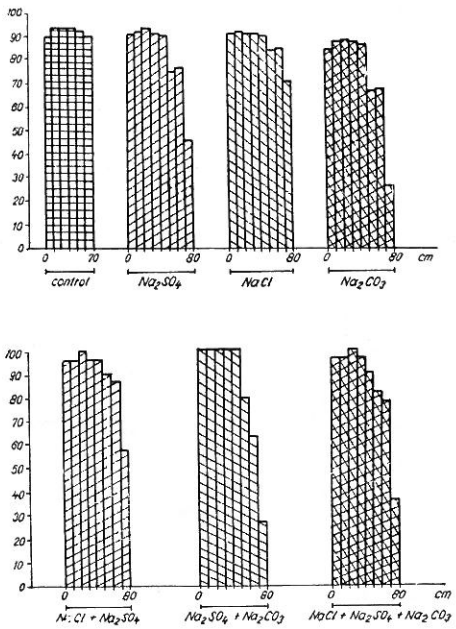

Fig. 17

The structure factor of VAGELER in the soils treated with different salt solutions

factor were lowest in the deeper horizons of soils treated with sodium carbonate and the next lowest values were found in the deeper layers of soils subjected to sodium sulphate treatment. If salt mixtures were employed the values had a transitional character as compared with the former.

In order to investigate further the physical properties, after the treatments in question the plasticity number of ATTERBERG [1] was determined in the deeper soil horizons. The results of these examinations are presented in Table 3.

Table 3

'Atterberg' plasticity number of the soils

Treatment	Depth, cm	Upper limit of plasticity	Lower limit of plasticity	Plasticity number
Untreated		39.97	18.15	21.82
NaCl	60—70	41.32	17.12	24.20
	70—80	42.56	16.92	27.64
Na_2SO_4	60—70	42.45	17.13	25.32
	70—80	43.15	18.18	34.97
Na_2CO_3	60—70	45.35	18.20	27.15
	70—80	47.17	10.18	36.99
$NaCl + Na_2SO_4$	60—70	42.36	17.45	24.91
	70—80	44.46	18.13	26.33
	80—90	43.14	17.15	25.99
$Na_2CO_3 + Na_2SO_4$	60—70	45.67	16.16	29.51
	70—80	46.13	17.09	28.04
	80—90	47.15	10.13	37.02
$Na_2CO_3 + NaCl +$ $+ Na_2SO_4$	60—70	43.07	16.92	26.15
	70—80	44.43	18.15	26.28
	80—90	46.67	17.13	29.54

As can be seen in this table, due to the effect of soda the plasticity number of ATTERBERG increased, while the neutral salts exercised less influence on it.

The water permeability of soils were also determined. Figure 17 presents the values of water permeability in soils treated with different salt solutions, measured in the layer situated at a depth of 70—80 cm. As the data of this figure clearly show, the neutral sodium salts decreased the degree of water permeability as compared to the control, but not significantly. The situation was quite different if we examined the water permeability value in a soil treated with the Na_2CO_3 solution. In that case it was practically reduced to zero, that is, due to the effect of the sodium carbonate solution, the physical properties of this soil layer changed to such an extent that the soil became practically impermeable. This fact is in full accordance with field experiences, showing that salt affected soils, developed under the influence of Na_2CO_3, have extremely poor water permeability.

The above described experiment shows how some of the particular effects of sodium salts capable of alkaline hydrolysis on the properties of soils greatly differ from those exerted by neutral sodium salts.

Some of the colloid chemical effects of various sodium salts — were investigated by SZABOLCS & DARAB [47, 50] and DARAB [10] with radioactive tracers. In order to characterize some of the reactions of soil colloids, with neutral sodium salts and sodium salts capable of alkaline hydrolysis, experiments were conducted with bentonite.

It may be seen in Figure 18 that — at varying Na concentrations — the curves of the uptake of labelled Na were similar for NaCl and Na_2SO_4 while that for Na_2CO_3 was different. It must be noted, that the differing characteristics of the curve are most prominent at a relatively low concentration range of sodium carbonate, while at considerably higher concentrations the curve draws near those of sodium sulphate and sodium chloride. This also supports the former statement that there is a certain, relatively low concentration of sodium salts capable of alkaline hydrolysis that determines soil colloidal processes leading to the formation of solonetz soils.

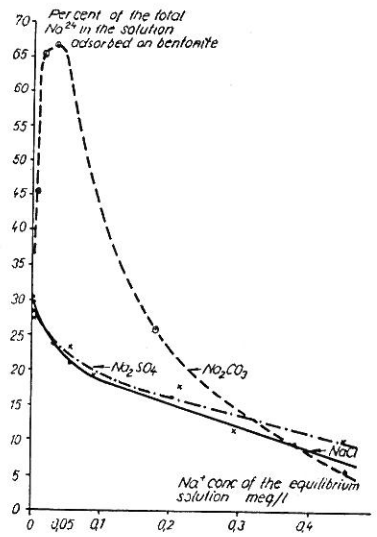

Fig. 18

Activity taken up by bentonite in the percentage of initial activity as a function of the equilibrium Na^+ ion concentration in bentonite — Na salt solution systems

In the course of the experiment the swelling of bentonite treated with sodium carbonate solution was also studied. Figure 19 clearly indicates that swelling reached its maximum at a relatively low concentration of sodium carbonate while at higher concentrations it assumed a nearly constant, lower value.

The time of thyxotropic setting of bentonite - sodium carbonate solution systems as affected by various Na concentrations was also investigated at various ratios of bentonite to solution. The results are presented in Figure 20. As with Figures 18 and 19 this also indicates that the time of thyxotropic setting was shortest in the relatively low concentration range of sodium carbonate.

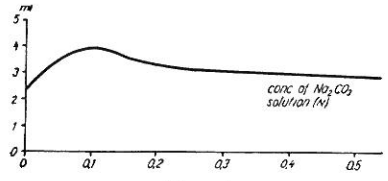

Fig. 19

Swelling of bentonite suspension

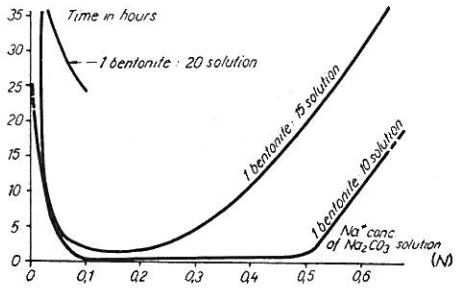

Fig. 20

Time of thyxotropic setting of bentonite — Na_2CO_3 solution system as a function of the solution concentration

Table 4

The change of the electrokinetic potential in 1 : 100 bentonite-Na_2CO_3 solution suspension as a function of the Na_2CO_3 solutions' concentration

Concentration of Na_2CO_3 solution (N)	Electrokinetic (ζ) potential (mV)
0	25.6
0.005	44.2
0.010	60.8
0.050	63.0
0.100	66.4
0.250	55.6
0.500	51.9
0.750	48.1

The electrokinetic potentials were determined by measuring the electrophoretic migration velocity in suspensions of bentonite and Na_2CO_3 solutions of different concentrations.

The change of the electrokinetic potential in 1 : 100 bentonite - sodium carbonate solution suspension as affected by various sodium carbonate concentrations was also measured and the data are given in Table 4. The data clearly show that it was again at relatively low concentrations of sodium carbonate that the electrokinetic potential reached the maximum values.

The above described colloid chemical experiments seem to prove that particular colloidal changes — which are necessary for solonetz forming processes — occur due to the effect of comparatively dilute solutions of sodium salts capable of alkaline hydrolysis.

The various effects of sodium carbonate on the physical, physico-chemical, chemical and biological soil properties have been studied and discussed by numerous experts (KOVDA [26], KELLEY [23], SZABOLCS [44, 45], GEDROITZ [14], ARANY [4], RATNER [36] and others) but the conclusive and comprehensive investigation on their connection with soil forming processes as well as on their influence on soil fertility and plants needs continued, extensive and co-ordinated international research work.

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